



# **Mars Atmosphere Effects on Arc Welds: Phase 1**

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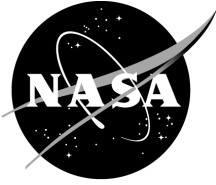
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## LIST OF SYMBOLS AND ACRONYMS

CO <sub>2</sub>	carbon dioxide
D/W	depth/width
FZ	fusion zone
GTAW	gas tungsten arc welding

## TECHNICAL MEMORANDUM

### MARS ATMOSPHERE EFFECTS ON ARC WELDS: PHASE 1

#### 1. INTRODUCTION

NASA has been unprecedented in achieving its goals related to space exploration and furthering the understanding of our solar system. In keeping with this trend, NASA's current mission is to land a team of astronauts on Mars and return them safely to Earth. In addition to comprising much of the structure and life support systems that will be brought to Mars for the habitat and vehicle, titanium and aluminum can be found and mined on Mars and may be used when building structures.<sup>1</sup> Where metals are present, there will be a need for welding capabilities. For welds that need to be made quickly and are located far from heavy resistance or solid state welding machinery, there will be a need for basic arc welding. Arc welding has been a major cornerstone of manufacturing throughout the 20th century, and the portability and capability of gas tungsten arc welding (GTAW) will be necessary for repair, manufacturing, and survival on Mars. The two primary concerns for welding on Mars are that the Martian atmosphere contains high levels of carbon dioxide (CO<sub>2</sub>), and the atmospheric pressure is much lower than it is on Earth. The high levels of CO<sub>2</sub> in the Martian atmosphere may dissociate and produce oxygen in the arc and therefore increase the risk of oxidation. For simplification, atmospheric pressure will not be taken into account for this experiment.

For survival on Mars during this mission, the life support and water filtration systems must be kept operational at all times. In order to ensure that water filtration systems can be repaired in the event of an emergency, it is very important to have the capability to weld. The Orion capsule and Mars lander must also remain operational throughout the duration of the mission to ensure the safe return of the astronauts on the mission to Mars. A better understanding of welding in a Mars environment is important to ensure that repair welds are possible if the Orion capsule/Mars lander or water filtration system is damaged at any point while on the surface of Mars. The Orion capsule is made primarily of AA2219-T87, and the water filtration system is primarily Ti-6Al-4V, so the effect of the Mars environment on welding those materials must be known to reduce potential mission risk. GTAW is a portable process that can weld a versatile group of metals, so it has many potential applications for welding on Mars. Thus, missions to colonize Mars will depend on the capability to weld a strong, leak-tight joint. Metals are also likely to be used in support structures made of a lightweight and durable material. For this reason, it is important to understand the implications of welding in a Mars environment. A comparison of the Martian and terrestrial atmospheres are provided in table 1. Based on the elemental compositions, simulation of the Martian atmosphere can be made using primarily CO<sub>2</sub> gas.

Table 1. Typical composition of the Martian and terrestrial atmospheres.<sup>2,3</sup>

	<b>Nitrogen (%)</b>	<b>Oxygen (%)</b>	<b>Argon (%)</b>	<b>CO<sub>2</sub> (%)</b>	<b>CO (%)</b>
Terrestrial atmospheric composition	78	21	0.9	–	–
Mars atmospheric composition	2.7	0.13	1.6	95.32	0.08

## 2. EXPERIMENTAL PROCEDURE

The project was broken down into multiple phases, each of which will add parameters to the experiment. Phase 1 test matrix is provided in table 2. This phase consisted of eight autogenous bead-on-plate welds for both AA2219-T87 and Ti-6Al-4V. Of the eight welds, four were made with traditional terrestrial methods and four were made in a glove box purged with simulated Mars gas. A picture of the glove box is shown in figure 1.

Table 2. Experimental matrix for this phase 1 Mars welding experiment.

Phase 1	2219 Aluminum (Pure Tungsten Electrode, 1/8 in)							
Weld ID	AlWeld 1M	AlWeld 2M	AlWeld 3M	AlWeld 4M	AlWeld 1E	AlWeld 2E	AlWeld 3E	AlWeld 4E
Thickness (in)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Torch shield gas (argon) (ft <sup>3</sup> /hr)	40	30	20	10	40	30	20	10
Atmosphere	Mars	Mars	Mars	Mars	Earth	Earth	Earth	Earth
Weld current (A)	170	170	170	170	170	170	170	170
Testing	X-ray, macro/hardness							
Weld position	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat
Weld length (in)	6	6	6	6	6	6	6	6
Phase 1	Titanium (2% Thoriated Tungsten Electrode)							
Weld ID	TiWeld 1M	TiWeld 2M	TiWeld 3M	TiWeld 4M	TiWeld 1E	TiWeld 2E	TiWeld 3E	TiWeld 4E
Thickness (in)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Torch shield gas (argon) (ft <sup>3</sup> /hr)	40	30	20	10	40	30	20	10
Atmosphere	Mars	Mars	Mars	Mars	Earth	Earth	Earth	Earth
Weld current (A)	75	75	75	75	75	75	75	75
Testing	X-ray, macro/hardness							
Weld position	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat
Weld length (in)	6	6	6	6	6	6	6	6

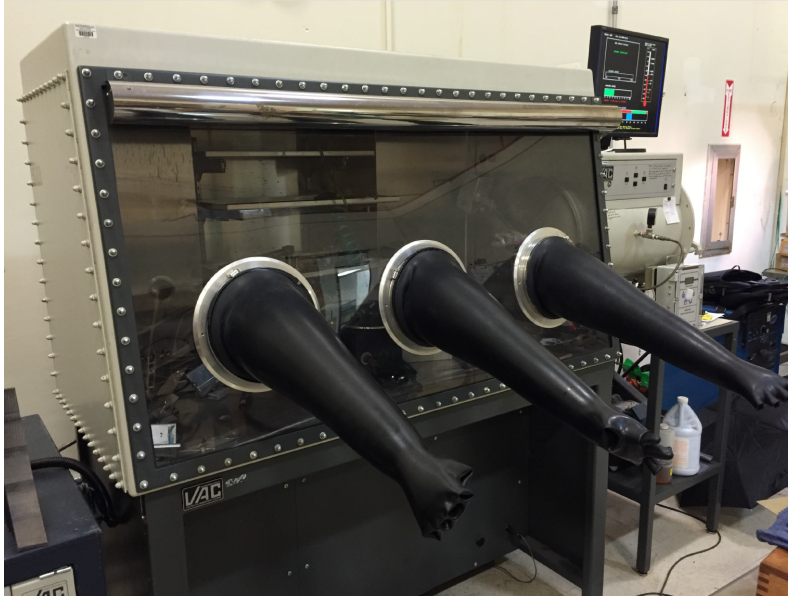


Figure 1. Purged glove box prior to beginning Martian welds.

The aluminum samples were made on 12-in-long  $\times$  8-in-wide  $\times$  0.25-in-thick plates, and the titanium samples were made on 12-in-long  $\times$  8-in-wide  $\times$  0.19-in-thick plates. Prior to welding, the panels were cleaned using a Scotch Brite® pad and wiped with acetone followed by isopropyl alcohol. All welds were made with a Miller Electric gas tungsten arc welding machine. Initial welds were made to optimize the current and travel speed for the GTAW process to be used for the welds. All the titanium welds were made with 75 A of current, and all the aluminum welds were made with 170 A of current. Each weld was 6 to 8 inches long to ensure that all of the necessary samples could be taken from each weld. Trial and error was used to optimize travel speed. Electrode material and size along with torch configuration were determined using prior knowledge of welding AA2219T87 and Ti6Al4V with GTAW. The argon shielding gas flow rate was adjusted from 10 ft<sup>3</sup>/hr to 40 ft<sup>3</sup>/hr.

The difference between the four terrestrial welds and four simulated Mars welds was the atmosphere. The simulated Mars welds were made in a glove box purged with a gas mixture similar to the composition of the Mars atmosphere, and the terrestrial welds were made in a typical Earth environment.

Following welding, the combined total of 16 welds were photographed and evaluated using radiography. After radiography, each weld was sectioned, mounted, polished, and etched, so they could be analyzed with an optical microscope. The primary purpose of the optical images was to show variations in fusion zone (FZ) penetration and color. Then, the eight titanium weld plates were cut into 2-in  $\times$  2-in pieces, so the FZ could be sent out to determine the levels of oxygen and nitrogen that were absorbed during welding. This was done according to ASTM E1409 and ASTM E 1019 using a LECO® analyzer TCH600.<sup>4,5</sup> After all 16 welds were imaged by the optical microscope, the mounted samples all had two or three hardness tests taken in the center of the FZ and the heat-affected zone. Excess weld material was kept in case more samples are needed.

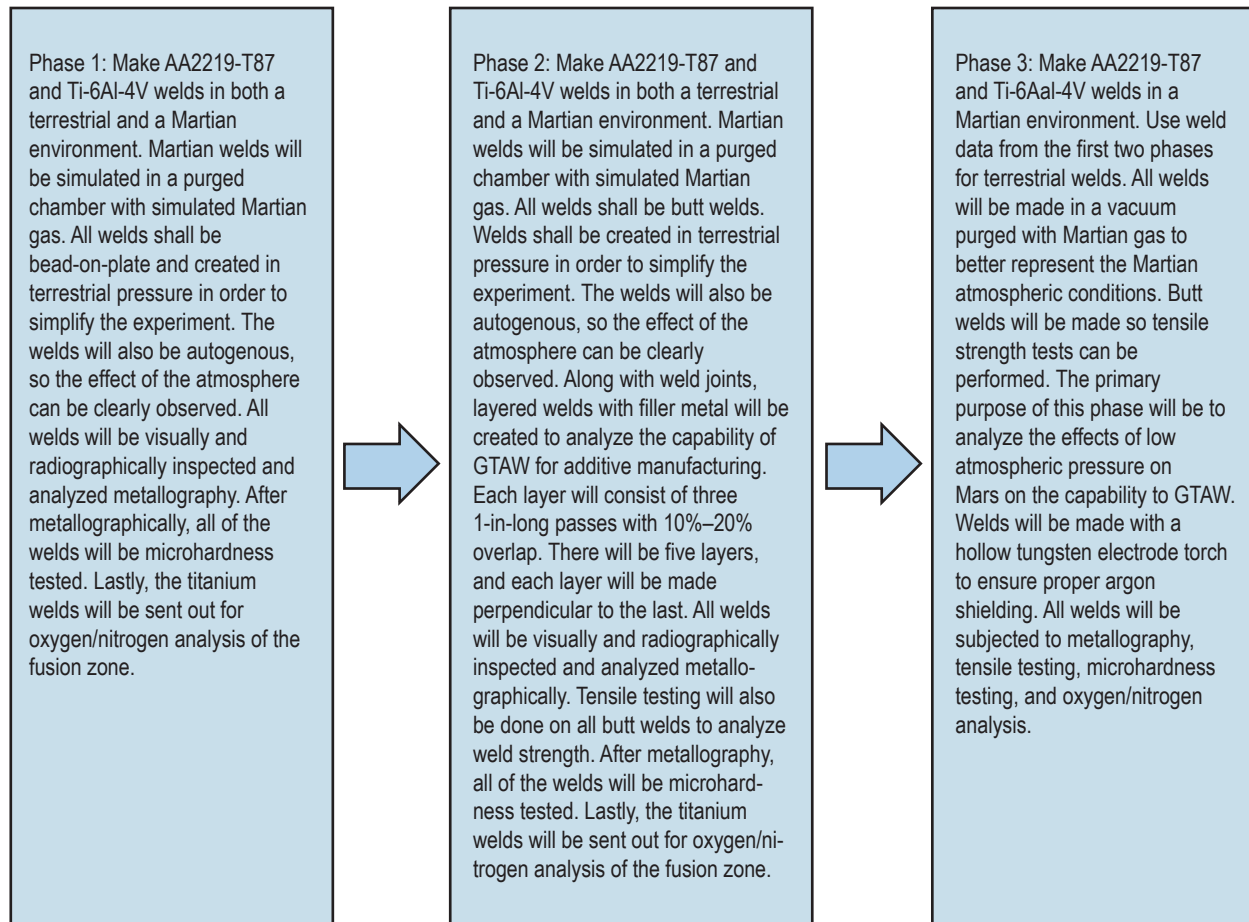


Figure 2. Flow chart describing the basic elements of each phase of this experiment.

### 3. RESULTS

As referenced in table 1, the Martian atmosphere contains high levels of CO<sub>2</sub>, which during welding, may introduce oxygen into the molten weld pool and therefore increase the risk of weld defects such as oxide strings or porosity. The level of nitrogen in the terrestrial atmosphere is far greater than in the Mars atmosphere so nitrogen contamination may be higher in terrestrial welds.

For all titanium welds, a gas lens was used to better distribute the argon shielding gas. All welds were made using direct current electrode negative. All titanium welds were made with a 3/32-in thoriated tungsten electrode and all aluminum welds were made with a 1/8-in pure tungsten electrode. The electrodes were all ground to a pointed tip prior to welding. All terrestrial welds were made with an HW20 torch and a #7 shielding cup. All Mars welds were made with an HW20 torch and ceramic shielding cup.

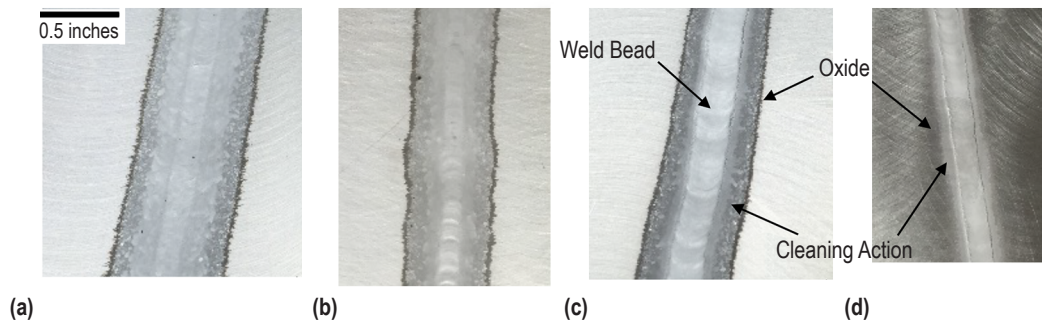


Figure 3. Images of AA2219-T87 welds right after weld completion: (a) AlWeld1E, (b) AlWeld1M, (c) AlWeld4E, and (d) AlWeld4M.

The welds were then mounted for metallographic examination using optical microscopes. The samples were welded both in open air and in a chamber purged with a gas mixture similar to the atmosphere on Mars. Figure 4 shows the images taken of the AA2219-T87 welds.

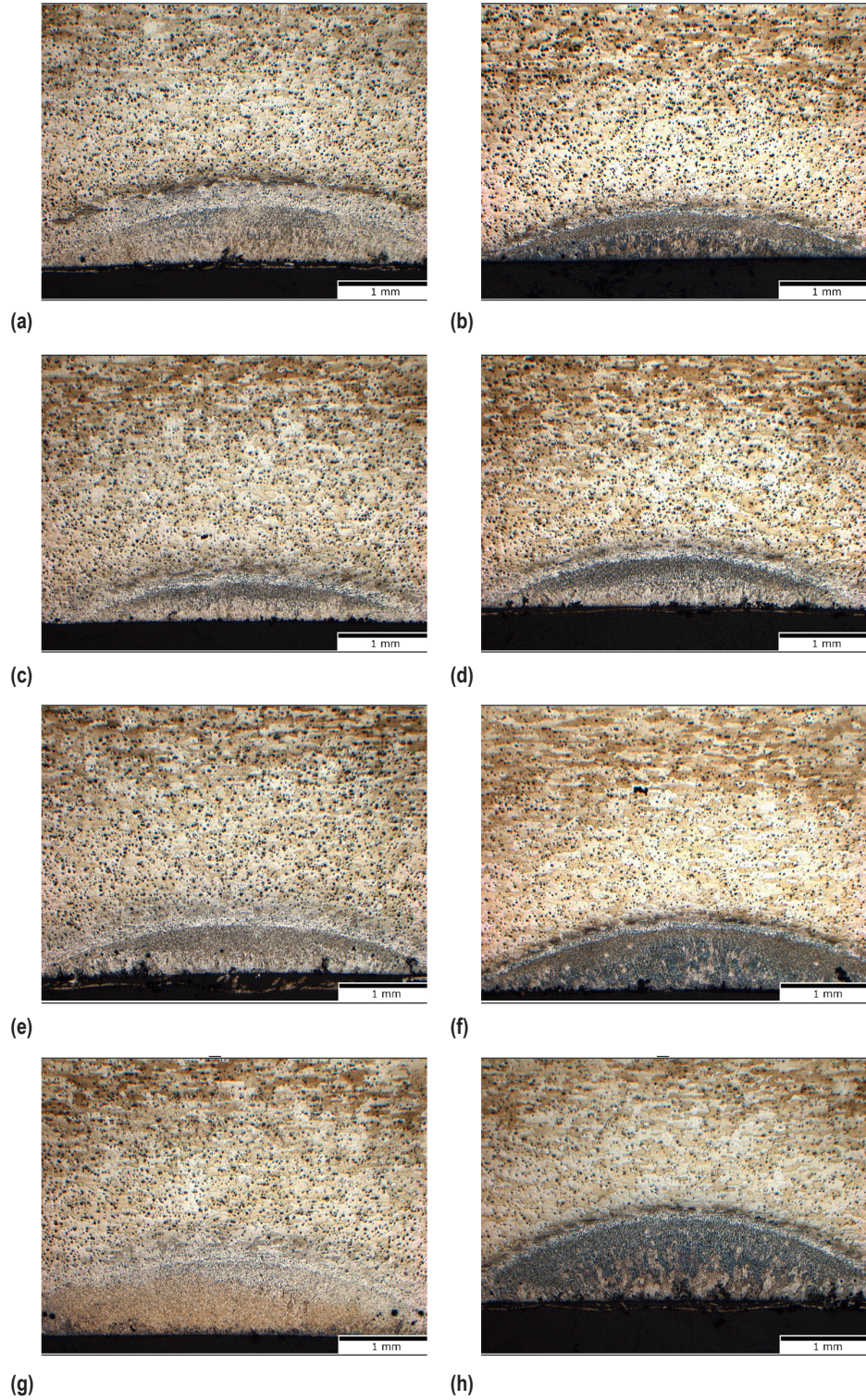


Figure 4. Optical images of AA2219-T87 samples: (a) AlWeld1E\_E25X (b), AlWeld1M\_25X, (c) AlWeld2E\_25X, (d) AlWeld2M\_25X, (e) AlWeld3E\_25X, (f) AlWeld3M\_25X, (g) AlWeld4E\_25X, and (h) AlWeld4M\_25X.

Visual images were then taken for the titanium welds and four of them are shown below in figure 5.

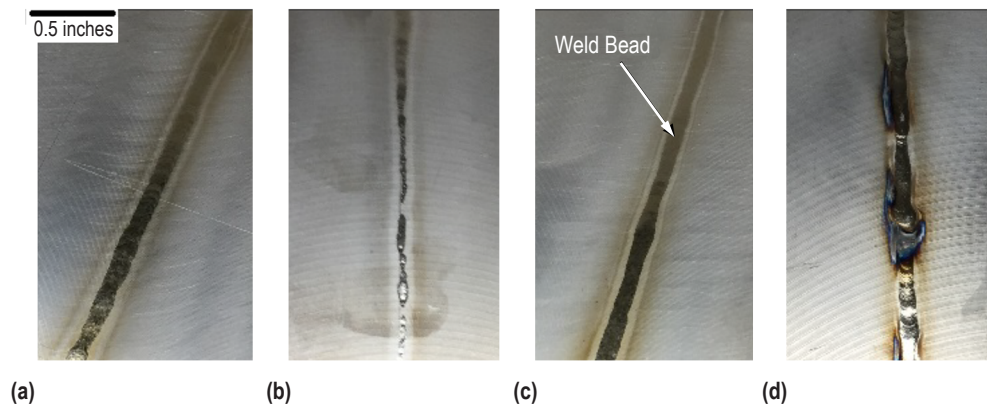


Figure 5. Images of Ti-6Al-4V welds right after weld completion: (a) TiWeld1E, (b) TiWeld1M, (c) TiWeld4E, and (d) TiWeld4M (images on same scale).

The titanium welds were then sectioned and metallographically mounted for optical examination. The samples were welded both in terrestrial air and in a chamber purged with a gas mixture similar to the atmosphere on Mars. Figure 6 shows the images taken of the Ti-6Al-4V welds.

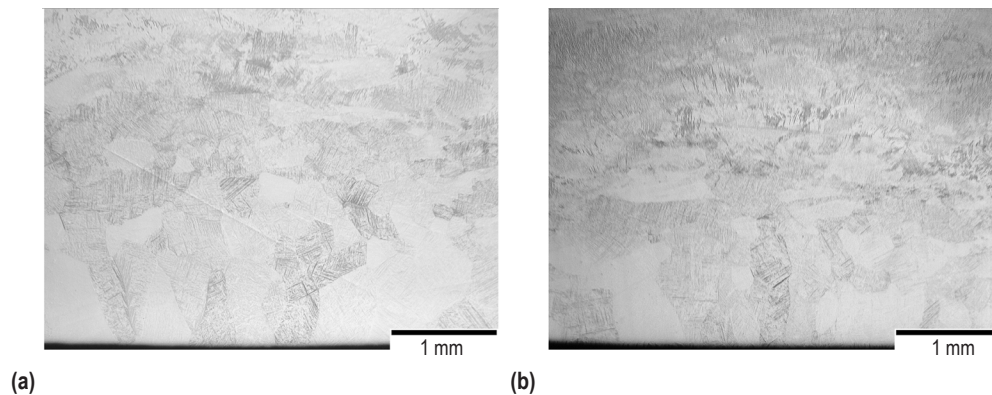


Figure 6. Optical images of welded Ti-6Al-4V samples: (a) TiWeld2E\_25X, and (b) TiWeld2M\_25X.

The Mars and terrestrial Ti-6Al-4V welds show no clear variation in weld microstructure or color in the cross sections. The affinity for oxidation is much lower in Ti-6Al-4V than in AA2219-T87 so the weld metal in both TiWeld2E and TiWeld2M is not clearly oxidized.

Next, radiography was conducted to nondestructively evaluate the entire weld. Images for both AA2219-T87 and Ti-6Al-4V welds are shown in figure 7. No evidence of internal defects were noticed in the radiographic images.

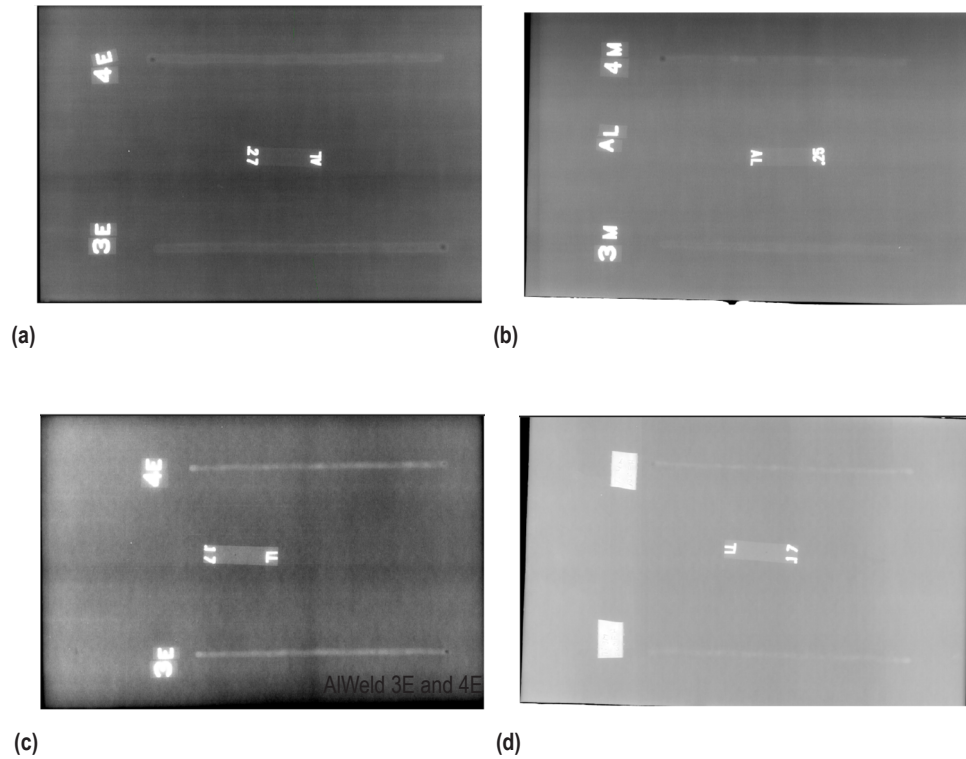


Figure 7. Radiographic images for a few of the welds made in this experiment: (a) AIWeld3E and 4E, (b) AIWeld 3M and 4M, (c) TiWeld 3E and 4E, and (d) TiWeld 3M and 4M.

Depth and width (D/W) of all of the weld pools were measured and are shown in figure 8.

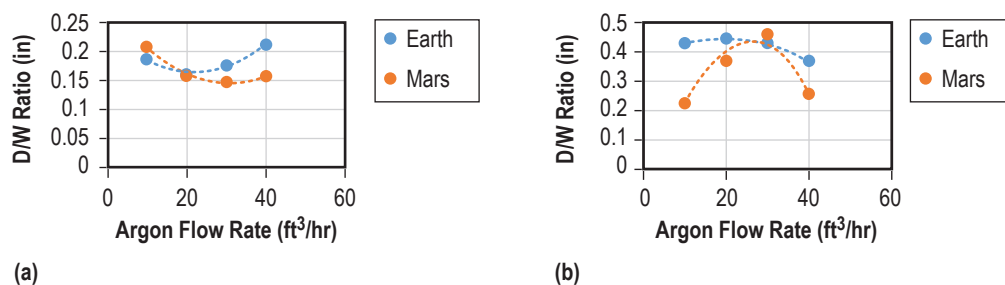


Figure 8. D/W ratios for all welds created in comparison to argon gas flow rate: (a) AA2219-T87 welds and (b) Ti-6Al-4V welds.

Next, hardness testing was conducted on the metallographic samples. Figure 9 shows the hardness values captured for all of the welds made in this experiment. Images of where microhardness testing indentations were made within the weld fusion zone and heat-affected zone. (Indentations labeled 1 were used for graphing FZ hardness.)

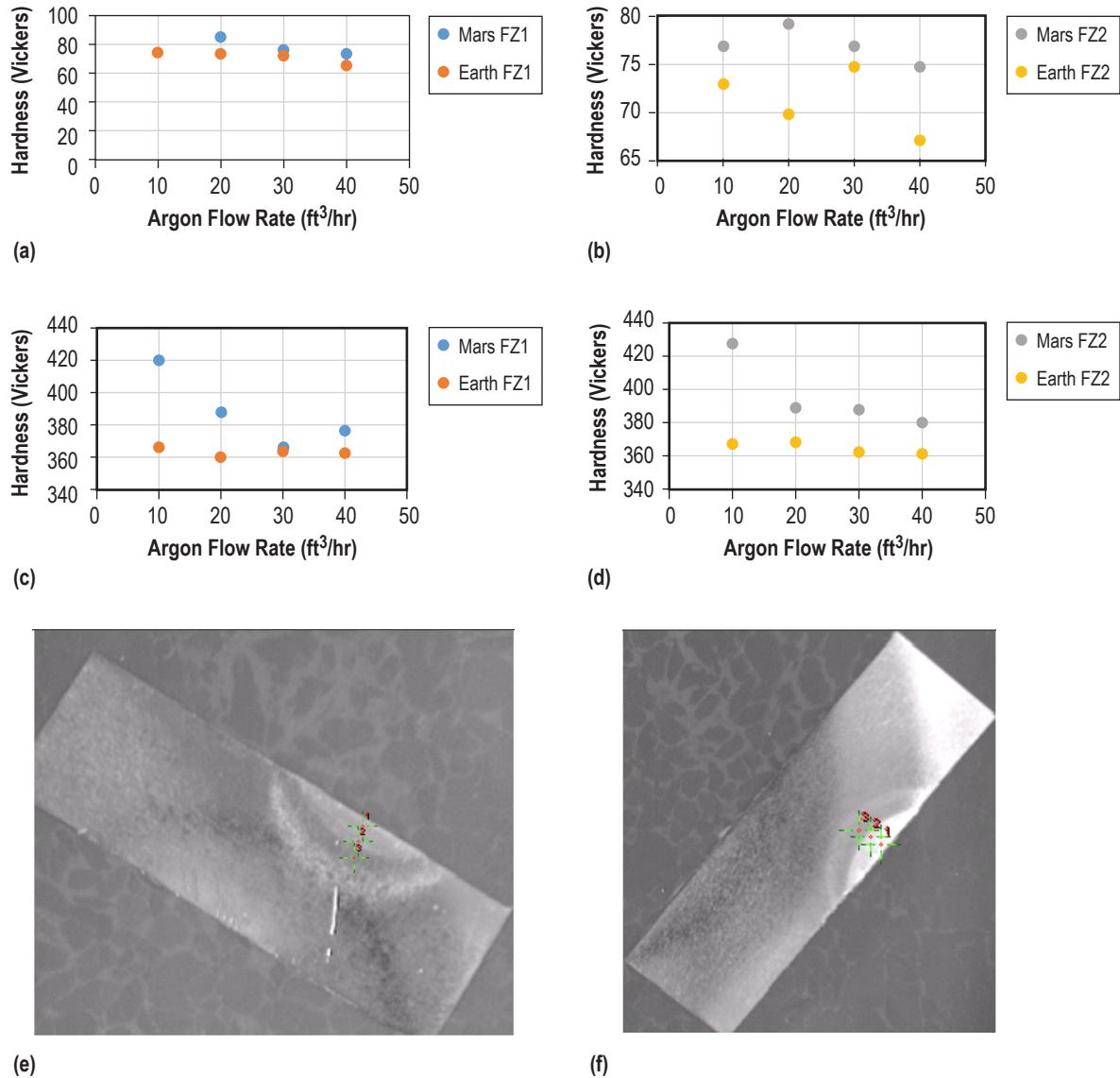


Figure 9. Hardness testing results in relation to argon flow rate for all Ti-6Al-4V and AA2219-T87 terrestrial and Mars welds: (a) AA2219-T87 FZ hardness test 1 (b) AA2219-T87 FZ hardness test 2, (c) Ti-6Al-4V FZ hardness test 1, (d) Ti-6Al-4V FZ hardness test 2 (e) AlWeld4E indentations, and (f) AlWeld4M indentations.

Oxygen and nitrogen analyses were conducted by Durkee Testing Laboratories according to ASTM E1409 and ASTM E1019 using a LECO analyzer TCH600. Results are shown in figure 10.

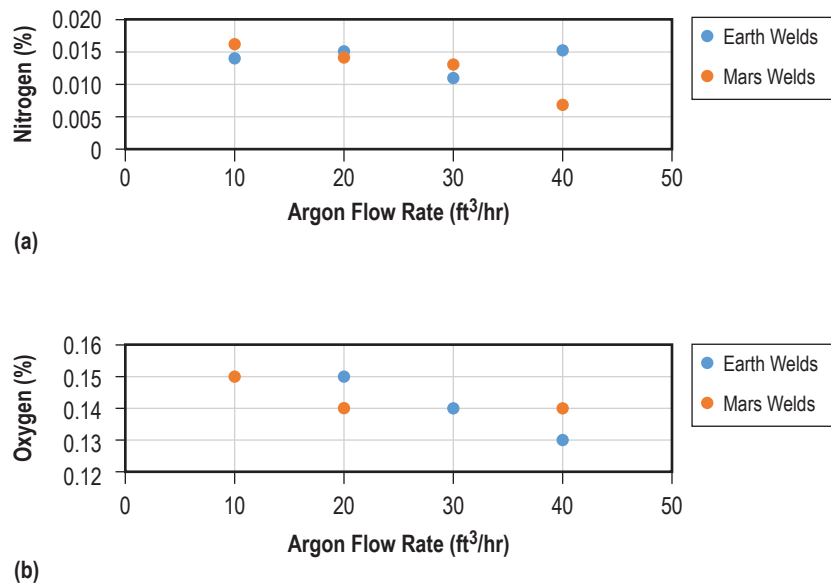


Figure 10. Levels of oxygen and nitrogen absorbed into the FZ of the welds in relation to argon gas flow rate: (a) Absorbed nitrogen in titanium terrestrial and Mars welds and (b) absorbed oxygen in titanium terrestrial and Mars welds.

#### 4. DISCUSSION

Figure 2 showed a flow chart briefly describing phases 1–3 of this experiment. Figure 3 showed an overview of the plan surface of the as-welded panels. The light regions outside the weld bead are the areas where the oxide layer is too thin to be visible. This indicates that oxide cleaning has occurred which is inherent to the alternating current GTAW process. The dark region outside the cleaned area is a remaining oxide buildup that was not cleaned during welding. As argon shielding gas flow rate decreased from AlWeld1E/1M to AlWeld4E/4M, the cleaning action also decreased. This decrease in cleaning action is more clearly observed in the simulated Mars welds with AlWeld4M showing less cleaning than AlWeld4E. This is attributed to a higher level of CO<sub>2</sub> contamination in AlWeld4M. A potential mechanism that may have decreased cleaning action in the simulated Mars welds may be related to the density difference of the environments. CO<sub>2</sub> has a density of 1.98 g/L and air has a density of 1.225 g/L. Since Mars gas is primarily CO<sub>2</sub>, the density of CO<sub>2</sub> is used to represent the density of Mars gas. The Mars gas has higher density in ambient conditions so it will impinge upon the argon shielding gas more than air, thus reducing the effectiveness of the argon shielding gas. Cleaning action occurs due to a buildup of positive ions on the oxide surface and the induced negative charge coming from inside the material. These opposing charges create an electric field across the oxide layer, and when the electric field reaches its breakdown level, the oxide is blasted off. The argon provides the positive ions necessary for cleaning action to occur, so greater levels of argon increase the extent of the oxide cleaning. The dilution of the exterior of the argon shielding plume will therefore reduce the width of the area where cleaning action will occur.

The pressure of the CO<sub>2</sub> is nearly five times the partial pressure of oxygen in the air for this study. During welding, the CO<sub>2</sub> in the simulated Mars atmosphere breaks down into carbon monoxide and oxygen within the arc, thus causing oxidation. This causes the discoloration shown in the simulated Mars aluminum weld cross sections in figure 4 and the overview image of TiWeld4M in figure 5(d). Since the pressure of CO<sub>2</sub> in the Mars gas is much higher than that of the oxygen in air, the simulated Mars gas is likely to cause more oxidation.

The increased CO<sub>2</sub> contamination into the shielding gas may also allow for a thicker oxide layer to form, thus reducing the cleaning action in the Mars welds. Formation of a thicker oxide layer will require a higher breakdown level for the electric field to cause oxide cleaning and may therefore reduce cleaning action.

Figure 5 (b) and (d) show inconsistent heating of the weld in the titanium samples welded in a Mars gas environment. It is difficult to maintain weld puddle and consistent arc while welding titanium in a Mars gas environment. This is due to the high level of CO<sub>2</sub> in the Mars gas, which causes an unstable arc leading to inconsistent heating. Increased shielding gas for welds made in a Martian gas environment may reduce this effect.

For all of the aluminum samples, aside from those shown in figure 4 (a) and (b), the penetration is higher in the samples welded in a Mars gas environment. This may have been caused by increased CO<sub>2</sub> penetration into the arc in the Mars samples due to the higher density of CO<sub>2</sub>.<sup>6</sup> The CO<sub>2</sub> gas molecules dissociate within the arc due to high heat and recombine at the surface of the weld pool. This increases heat within the weld, therefore, increasing penetration. The surface tension gradients within the weld pool cause fluid flow from the surface of the weld pool. This is the mechanism for weld puddle movement and it strongly affects the penetration of a weld. The heat of the arc drives away contaminants which causes surface tension to increase at the center of the weld pool.<sup>7</sup> This increase in surface tension causes the metal at the surface of the weld pool to flow inward causing the weld depth to increase. Samples AlWeld1E and AlWeld1M were both made with an argon gas flow rate of 40 ft<sup>3</sup>/hr, which was the highest level of shielding gas used. This higher level of shielding gas would mostly eliminate contamination from the atmosphere and therefore would decrease CO<sub>2</sub> contamination into the FZ of AlWeld1M. The simulated Mars welds also clearly show a blue color indicating oxidation. AlWeld4M clearly exhibits the darkest blue cross section which may have been caused by increased CO<sub>2</sub> contamination of the FZ due to decreased argon shielding gas.

Figure 6 shows the optical microscopy images for the 2E and 2M Ti-6Al-4V samples. These two samples are representative of all of the Ti-6Al-4V samples showing no clear difference between Mars and terrestrial welds.

Depth/width ratios are higher in most terrestrial welds created. The Mars welds exhibit a slightly higher D/W ratio for the AA2219-T87 weld made at 10 ft<sup>3</sup>/hr and the Ti-6Al-4V weld made at 30 ft<sup>3</sup>/hr argon flow rate. TiWeld2M was made at 30 ft<sup>3</sup>/hr and was the titanium weld made in the Mars environment that had the highest penetration as observed with visual inspection of the weld. Two potential phenomena may cause the observed variations in D/W ratios. First is the Marangoni effect which would, on its own, cause reduced D/W ratios at higher argon flow rates.<sup>7,8</sup> This effect appears to be dominant in the Ti-6Al-4V samples which do show a decrease in D/W ratio at higher argon flow rates. The second effect may be dependent on the metal itself, and for AA2219-T87, higher argon flow rates increase weld penetration depth. The effect of the simulated Martian gas appears to shift the D/W ratio slightly downward.

As shown in figure 9, the Mars welds consistently exhibit higher hardness in the FZ. The hardness levels are clearly higher in all of the titanium Mars welds than the titanium terrestrial welds, and at lower shielding gas flow rates, the hardness variation is greater. This may be attributed to higher atmospheric contamination at lower argon shielding rates.<sup>8</sup> The CO<sub>2</sub> in the Mars environment has a greater effect on hardness than the nitrogen and oxygen in the terrestrial environment due to variation in specific heat.<sup>9,10</sup> Nitrogen content must also be considered because it has similar affects as oxygen on the weld metal hardness.

According to figure 5, Mars welds simulated on titanium consistently exhibit thinner weld beads. At lower argon shielding flow rates they also exhibit discoloration which may be caused by uneven heating and contamination from CO<sub>2</sub>. The CO<sub>2</sub> in the Mars environment affected the arc stability, but oxygen was not absorbed into the weld metal as seen in the aluminum weld cross sections.<sup>6</sup>

The data shown in figure 10(b) on absorbed oxygen in the FZ of all of the titanium welds show no significant variation in oxygen levels between the Mars and terrestrial welds. Despite this lack of variation in absorbed oxygen, there is a clear variation in hardness between the Mars and terrestrial titanium welds as shown in figure 9. The Mars welds consistently exhibit higher hardness especially at low argon flow rates. The decreased argon shielding and higher density  $\text{CO}_2$  allows for increased contamination from the atmospheres which may have caused increased hardness in the Mars welds.<sup>11</sup> The instability of the arc in  $\text{CO}_2$  would have also caused inconsistent heating which could have led to increased cooling rates that increased the hardness levels.<sup>6</sup>

The absorbed nitrogen levels are relatively consistent for all of the titanium welds indicating that contamination from the Mars gas environment is more severe because nitrogen levels are 2.7% in the Mars gas, which is much lower than the value of 78% in the terrestrial atmosphere. Greater density of the Mars gas compared to the air on Earth may have caused the increased atmospheric contamination found in the Mars welds. The methods used to measure absorbed nitrogen was consistent for all titanium welds so any margin of error is consistent throughout all titanium samples. The method used was a LECO analyzer TCH600 as specified in ASTM E1409 and ASTM E1019.

The aluminum Mars welds have blue colored cross sections and exhibit higher hardness than the aluminum terrestrial welds. These observations may have both been caused by increased contamination from the atmosphere high in  $\text{CO}_2$ , since in aluminum,  $\text{CO}_2$  acts to oxidize the metal much more aggressively than in titanium. According to figure 10, the oxygen analysis of the FZ of the titanium welds shows no clear indication of higher oxygen levels in the Mars welds. The  $\text{CO}_2$  in the Mars environment may have more directly affected the arc stability by adding oxygen to the arc but the oxygen was not absorbed into the weld metal. Absorbed nitrogen levels in the Mars titanium welds is very close to or greater than in the terrestrial titanium welds at flow rates below  $40 \text{ ft}^3/\text{hr}$ . This indicates that atmospheric contamination from the Mars atmosphere is greater than in the terrestrial atmosphere because the level of nitrogen on Earth is far greater than on Mars but the welds still exhibit similar amounts of nitrogen absorption. This affect may be initiated by the higher density of the Mars gas compared to the air on Earth, thus causing greater contamination of the shielding gas by the atmospheric gas. The  $\text{CO}_2$  in the Mars atmosphere had a specific heat of 1.289 and the specific heat of air is 1.4. Specific heat is defined as, “the heat required to raise the temperature of the unit mass of a given substance by a given amount.”<sup>9</sup> The specific heat of  $\text{CO}_2$  is lower than air which indicates that  $\text{CO}_2$  absorbs heat more quickly than air which could lead to an increased cooling rate in metals welded in a  $\text{CO}_2$  atmosphere.<sup>10</sup> This increased cooling rate would therefore lead to increased hardness within the metals.<sup>12</sup>

## 5. CONCLUSION

For this experiment, AA2219-T87 and Ti-6Al-4V were welded in both a terrestrial atmosphere and a simulated Mars atmosphere. The welds were compared by color, shape, hardness and absorbed gases. Simulated Mars atmosphere welds were found to consistently exhibit higher hardness in both materials. Hardness levels were also found to be higher in all welds made using a lower level of argon shielding. At lower levels of shielding, the atmosphere contaminated the welds more greatly. The CO<sub>2</sub> in the simulated Mars atmosphere would increase oxidation of the weld and would therefore cause blue discoloration in the simulated Mars welds. The simulated Mars welds appeared to have a higher level of atmospheric contamination into the argon shielding gas which may have been caused by an increased density of Mars gas compared to terrestrial air.

The CO<sub>2</sub> in Mars gas caused arc instability leading to inconsistent heating which could attribute to changes in cooling rates, thus affecting hardness values. The specific heat of CO<sub>2</sub> is lower than that of air which may also lead to increased cooling rates, thus increasing hardness values in the simulated Mars weld samples compared to the terrestrial weld samples. With regards to hardness and weldability, welds may be made in a simulated Mars environment using increased argon shielding to reduce CO<sub>2</sub> contamination.

Further experimentation must be done in follow-on project phases to determine what the Martian environment does to GTAW with regards to mechanical properties. Future experiments shall also take atmospheric pressure into account to better represent the Martian environment, using techniques such as weld experiments in a partial vacuum.

Welding plays a major role in manufacturing throughout the aerospace industry. GTAW is a versatile technique that has the capability to weld many different metals with varying composition. For future missions to Mars, a portable technique such as GTAW would be highly useful in building structures and repairing vital water filtration components. For this reason, a better understanding of the difference between welding on Earth and on Mars must be understood. With a better understanding of the difference, a link can be drawn between all knowledge of welding on Earth and the future of welding on Mars.

Recommendation: Any phases beyond a second phase of this experiment will utilize vacuum, weld joints, and layered gas tungsten arc welds to test the feasibility of GTAW on Mars.



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